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Optimization of self-regulated hydrogen production from photovoltaic energy

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ABSTRACT

The use of photovoltaic energy (PV) for the production of hydrogen by using autonomous modular self-regulated systems is studied. Results are compared with those obtained for controlled systems. It was proved that for small and low-cost applications, it is possible to eliminate any control system with yields as high as 91.2% in the PV-electrolyzer interface for a sunny day. Self-regulated systems are thus an excellent, safe, cheap and environmentally friendly alternative for applications in isolated sites, especially in emerging countries.

Introduction

The use of renewable and clean energy is an essential objective for the subsistence of the global ecosystem [1,2]. However, due to the discontinuity and limitation of the total available resource, priority is given to the development of increasingly efficient methods of capture, conversion and storage [3–5]. In this sense, the hydrogen vector is a promising medium for storing and regulating the availability of renewable forms of energy [6–11]; particularly, the development of advanced materials that allow the improvement of processes for hydrogen storage and conversion is continuously reported [12,13]. In previous papers, other authors and we proposed the use of self-regulated systems with minimal use of control systems. These arrangements could be very useful for energetically isolated (off-grid) settlements [14,15].

In the current state of the art, it is clear that the greatest advances in yield are expected from the photovoltaic stage: the systems in use today convert between 15 and 30% of the total incident radiant energy, depending on the technology [16]. On the other hand, the systems for generation of hydrogen by electrolysis have been studied for a long time, having achieved very important yields thanks to its optimization and the development of new technologies [17–23].

Parallel to this progress is the research on the most efficient way of managing this energy through refined algorithms, simulations, applying artificial intelligence and neural networks [24–32]. Both the methods of detection of maximum power in photovoltaic (PV) capture systems and those of

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administration for consumption or storage are being carefully studied in recent years [21,26,33–35]. In particular, by optimizing the PV capture by the detection of the maximum power point (MPP) and the production of hydrogen by the study of electrolyzer response, coupled with permanent research to optimize the obtention and accumulation of hydrogen, it is possible to take advantage of the energy captured more and more efficiently [12,13,36].

Although these control systems allow to optimize performance in large, medium and even small renewable energy systems (houses, isolated stands, small towns) it is interesting to study the limits of self-regulated systems for small applications, ie modular systems that through an appropriate design, are able to manage the provision of energy from primary sources with high performance [14].

Taking into account the simplification of systems and the economy and robustness of the sets, it is possible to expect cases where it is convenient to evaluate the application of a self-regulated system instead of a controlled one; this possibility will depend on the geographic location, the conditions of installation and maintenance. In this way it is interesting to know the expected performance, the limits of application and the validity of a self-regulated system and compare it with the characteristics of a controlled system.

The efficient use of primary energies involves the optimization of the methods of capture and conversion, each of them with their associated losses. Control systems and interfaces cause very important energy losses; in addition, the weight and structure of these systems increases as the scale of work is reduced [21,33–35].

This work analyzes the application of photovoltaic solar energy for the production of hydrogen by means of power management using autonomous modular self-regulated ("taylored") systems. The application limits obtained with these systems are compared with those obtained for controlled systems, which are continuously studied and optimized [33–35,37–40].

Experimental

For photovoltaic solar capture, three KS3T and three KS64TA polycrystalline photovoltaic modules provided by Solartec were used; the technical characteristics reported by the manufacturer are shown in Table 1.

To convert the electrical energy produced into storable H_2, four alkaline electrolyzers, based on a prototype previously developed in our laboratory, were used [15]. Each device consists of two concentric electrodes made of plates of stainless steel 310 (2 mm thick) immersed in an aqueous solution of 30% w/w KOH. Placed between the electrodes is a cylindrical acrylic tube, which keeps the gases from mixing. The whole system is hermetically sealed in a tube whose top cap allows electrical connection and the output of H_2 and O_2. The power supplied to the electrolyzer by the solar panels is used to split water into gaseous H_2 and O_2.

Current and potential measurements were carried out with two True RMS 189 Fluke Multimeters; a Fullenergy HY3020 DC Power Supply was used for the characterization of the electrolyzers; solar radiation intensity was measured with a ST-1307 Solar Power Meter.

For the calculations of tuned high-efficiency systems, data from the following suppliers were used:

Fuel Cell Store Electrolyzer Hardware – Round Model 900 [41].

Panasonic HIT330 VBHN330SJ47 PV modules [42].

The characteristic data are presented in Table 2 and Table 3, respectively.

Table 1 – Characteristics of 3 W and 64 W photovoltaic modules used in this work.

	KS3T-6V	KS64TA
Max. power (Pmax) [W]	3	64
Max power voltage (Vmp)[V]	8.70	15.60
Max. power current (Imp) [A]	0.36	4.10
Open circuit voltage (Voc) [V]	10.50	18.80
Short circuit current (Isc) [A]	0.42	4.40

Table 2 – Characteristics of electrolyzer [41].

Number of cells used	2
Active Area per Cell	50 cm^2
H_2 Production	90–900 std cc/min
O_2 Production	45–450 std cc/min
Current	6–60 A
Operating Voltage @ 40 A	4 V
H_2 Output Pressure (Max)	20 barg
O_2 Output Pressure	1 barg
Operating Temperature	20–55 °C

Table 3 – Characteristics of PV module [42].

Electrical data (at STC)	
Max. power (Pmax)	330 W
Max. power voltage (Vmp)	58.0 V
Max. power current (Imp)	5.70 A
Open circuit voltage (Voc)	69.7 V
Short circuit current (Isc)	6.07 A
Solar Panel efficiency	19.7%
Temperature characteristics	
Temperature	44.0 °C
Temp. coefficient of Pmax	−0.258%/°C
Temp. coefficient of Voc	−0.164 V/°C
Temp. coefficient of Isc	3.34 mA/°C
At NOCT (Normal Operating Conditions)	
Max. power (Pmax)	253.9 W
Max. power voltage (Vmp)	56.5 V
Max. power current (Imp)	4.56 A
Open circuit voltage (Voc)	66.0 V
Short circuit current (Isc)	4.91 A
At low irradiance (20%)	
Max. power (Pmax)	63.5 W
Max. power voltage (Vmp)	57.0 V
Max. power current (Imp)	1.12 A
Open circuit voltage (Voc)	65.6 V
Short circuit current (Isc)	1.22 A

STC, Standard Test Conditions: Air mass 1.5; Irradiance = 1000 W/m^2; cell temp. 25 °C
NOCT, Normal Operating Cell Temp.: Air mass 1.5; Irradiance = 800 W/m^2; Air temperature 20 °C; wind speed: 1 m/s; Low irradiance: Air mass 1.5; Irradiance = 200 W/m^2; cell temp. = 25 °C

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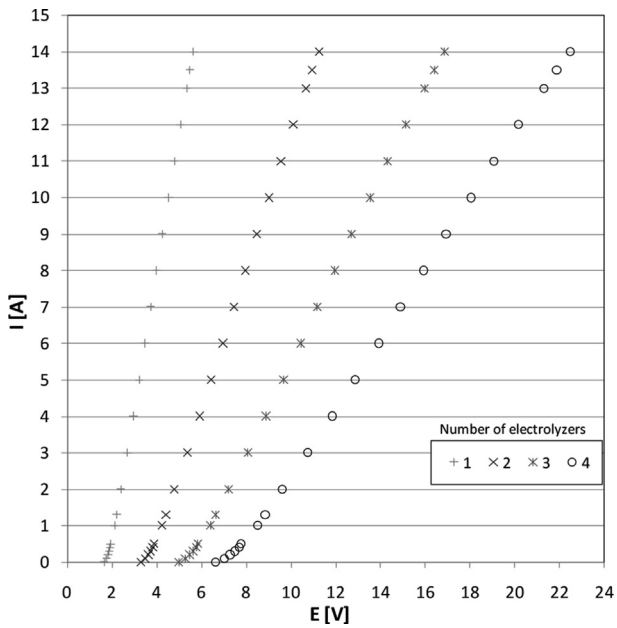

Fig. 1 – Discharge curves (I–V) for one to four electrolyzers connected in series.

Results and discussion

In Fig. 1 the I–V curves of one to four electrolyzers connected in series are shown; these curves were superposed to those obtained for the KS64TA (Fig. 2) and KS3T-6V (Fig. 3) modules; for both sets of modules parallel connections were used. Fig. 2 shows the coincidence between the point of maximum power of the three KS64TA PV modules with the discharge curve of three electrolyzers connected in series (see unfilled circle in Fig. 2). Fig. 3 shows that the same is true for the three KS3T-6V PV modules and 4 electrolyzers. This means that for those specific conditions, the configuration is optimal in terms of power delivered to the electrolysis system. However, two issues need to be considered:

1) Of the total energy delivered to the electrolyzers only that determined by the dissociation voltage of the water produces hydrogen (vertical dotted lines in Fig. 2; the vertical full lines indicate the thermo-neutral reaction voltage). The excess voltage in each case represents power dissipation without hydrogen production. This low efficiency of the electrolyzers is represented in the annexed pie charts: it is observed that although the maximum power of the KS64TA is delivered to the electrolyzers, only 24% produces hydrogen, whereas the KS3T-6V working in the low-power electrolyzer input yields 58%.
2) To the disadvantage mentioned above should be added the fact that the low slope of the curves of the electrolyzers are

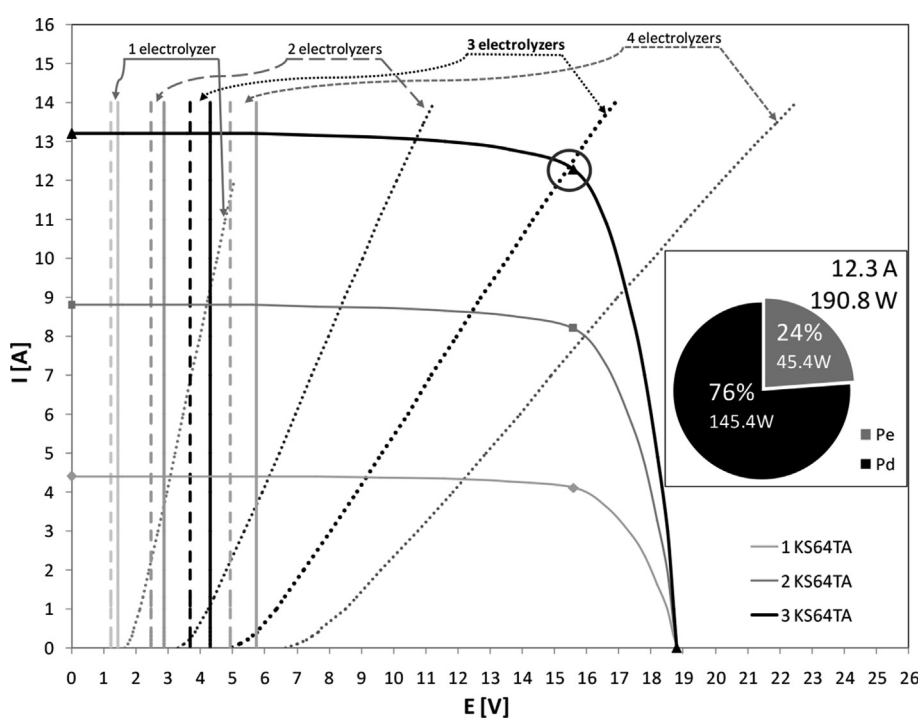

Fig. 2 – Superimposed graphs of the electrolyzer discharge curves with the I-V curves of the KS64TA modules delivering their maximum power (1 module, 2 and 3 modules connected in parallel). The water dissociation potentials (dashed lines) and thermo-neutral electrolysis (full line) are also included as reference. Pie chart: Performance in hydrogen production of the power used in the electrolyzers (Pe = actual power, Pd = dissipated power) for the maximum power point delivered by the modules to the electrolyzer (circle shown in the I-V graph).

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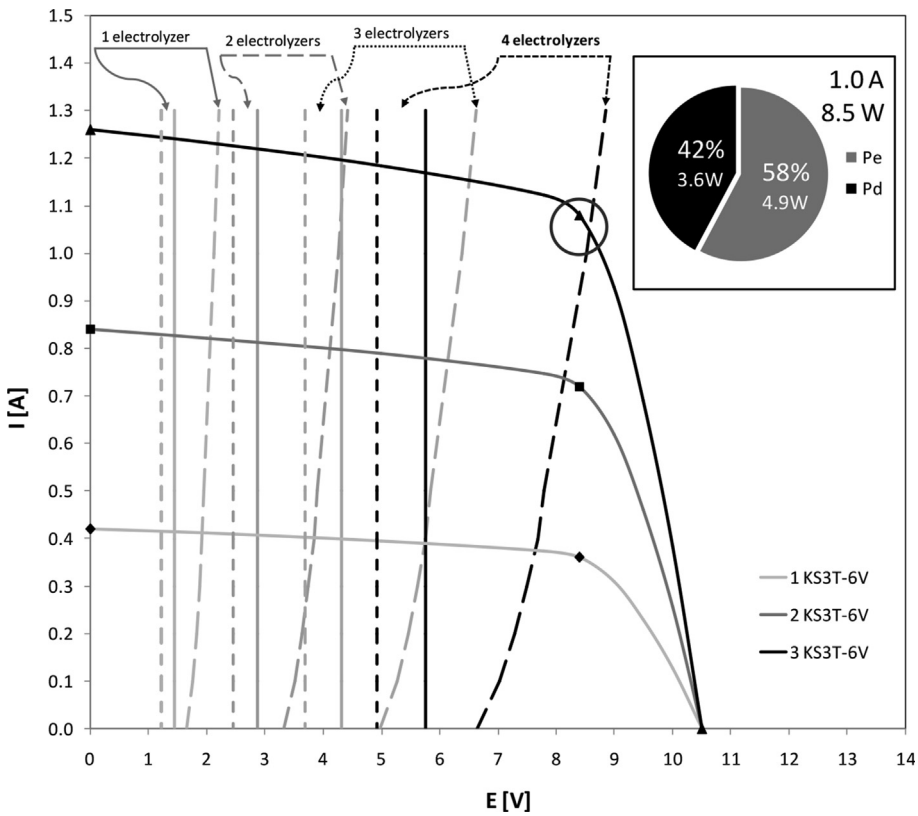

Fig. 3 – I-V curves for the KS3T-6V modules (one to three modules connected in parallel) superimposed with the same electrolysis curves described in Fig. 2. Pie chart: see caption in Fig. 2.

too far away from the variations in response of the photovoltaic modules, either by variation of irradiance or by variation of temperature.

Even under these considerations it is possible to calculate the variations of performance at low demand of the electrolyzers; from this it is possible to estimate the percentage variation of the yield due to the irradiance fluctuation.

As is well known, the variation in irradiance affects mainly the current and to a much lesser extent the voltage delivered by the modules.

For the configuration shown in Fig. 3, yields above 94% in the range of 1000 to 300 W m^{-2} of irradiance are obtained. This

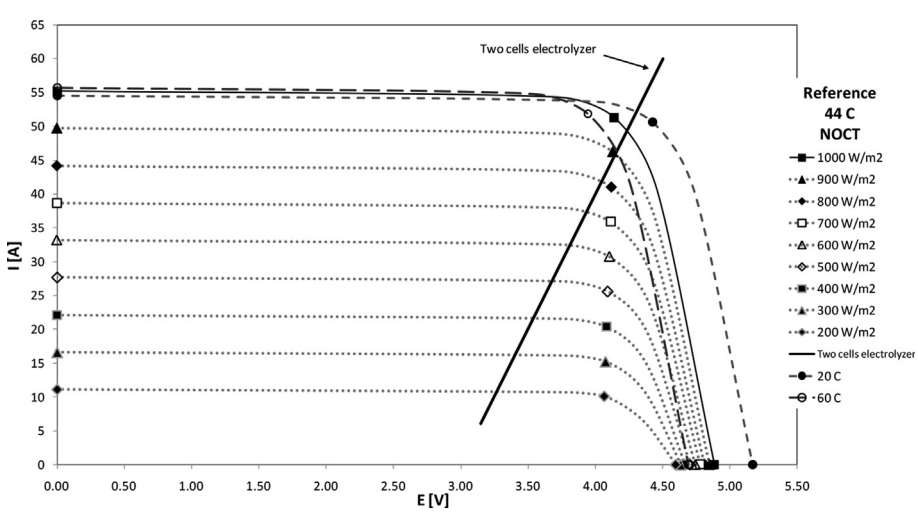

Fig. 4 – Curves at different irradiances for 9 modules connected in parallel; each module consisting of seven cells connected in series and discharge curve of a commercial two-element membrane electrolyzer operating between 6 and 60 A (black straight line).

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is a highly promising result: practically all the power generated by the PV modules is delivered to the electrolyzers.

In order to perform the complete analysis of the system and its behavior against irradiance and temperature variations, it is necessary to consider electrolysis devices according to the state of the art already mentioned above [41].

Fig. 4 shows the I–V evolution of a commercial two-element membrane electrolyzer operating between 6 and 60 A (Fuel Cell Store, Round Model 900; black straight line) [41]; Fig. 4 also shows the curves at different irradiances for 9 modules connected in parallel; each module consisting of seven cells connected in series (data from Ref. [42]), which is a suitable configuration for the proposed electrolyzer. For the highest irradiances, a good fit between the devices is observed; the increase in loss is proportional to the fall in irradiance, with less influence on the total daily energy delivered for a complete clear day. For a quantitative verification of these observations, we perform the following analysis:

The results of the calculations for a particular situation under specific conditions for a sunny day are shown in Table 4. Computations were made based on the following premises: considering maximum irradiance at noon (1000 W m^{-2}), the day was fractionated in periods of 1.5 h, centered at noon; from this one takes symmetrical segments towards the dawn and dusk (2 × 1,5 h = 3 h), which gives a total of 13,5 h of usable irradiance. For these periods, reference irradiance values between 200 and 800 W m^{-2} were calculated based on the normal operating cell temperature (NOCT) response. Table 4 shows the voltage, current (at MPP) and the power that the PV set can deliver at each period of the day. Then, using the following procedure, the charge line of the electrolyzer is used to establish the minimum power point on the electrolyzer: if the resistance of the electrolyzer limits the current flow generated by the PV modules (i.e., the straight line of the electrolyzer cuts the PV curve to the right of the MPP) the MPP voltage is used and the current in the electrolyzer is calculated for that voltage; on the other hand, if it produces the voltage drop of the modules (i.e., the electrolyzer line cuts the PV curve to the left of the MPP), the MPP current is used to calculate the voltage and power in the electrolyzer. The results show that the daily average photovoltaic utilization by direct connection is 91.2%; if the average efficiency of the electrolysis step (75.1%) is considered, the total average energy conversion efficiency is 68.5%.

It must be considered that when working with solar energy there are variations due to atmospheric causes (mainly cloudiness) that can affect the performance of the system. In regulated systems this problem can be addressed by means of control devices and intermediaries (i.e. batteries) that can compensate for the effect of atmospheric variations. However in these cases it is important to avoid ripple and variations of high or even low frequencies, which can cause premature aging or damage of electrolyzers [43].

Variations due to climate in a self-regulated system and their effects on its overall performance should be investigated in accordance with the characteristics of the electrolyzers used. In the present study, the monopolar electrolyzers did not show a considerable drop in performance during periods

Table 4 – Analysis of PV-electrolyzer and total efficiency for hydrogen production in a sunny day at different daily times (the maximum irradiance value corresponds to the noon; see the text for a full explanation).

	Reference Values						Results								
	PV (at MPP)			Electrolyzer											
Irradiances	Voltage [V]	Current [A]	Power (Wpv) [W]	V at PV current value [V]	I at PV Voltage value [A]	Minimum power over electrolyzer [W]	Daily hours Time (Dt) [h]	Total PV energy delivered [Wh]	Total energy over electrolyzer [Wh]	PV-Electrolyzer coupling efficiency	Electrolyzer-H2 thermo-neutral energy [Wh]	Electrolyzer-H2 thermo-neutral efficiency	Total H2 thermo-neutral efficiency	Energy in H2 produced [Wh]	Electrolyzer-H2 production efficiency	Total efficiency in H2 produced
1000	4.14	51.36	212.49	4.28	45.49	188.23	1.5	318.74	282.34	88.6%	196.52	69.6%	61.7%	167.86	59.5%	52.7%
800	4.12	41.04	169.08	4.03	44.78	165.23	3	507.23	495.69	97.7%	354.59	71.5%	69.9%	302.88	61.1%	59.7%
600	4.10	30.72	126.03	3.77	44.07	115.75	3	378.08	347.25	91.8%	265.45	76.4%	70.2%	226.74	65.3%	60.0%
400	4.08	20.41	83.35	3.51	43.36	71.61	3	250.04	214.83	85.9%	176.32	82.1%	70.5%	150.61	70.1%	60.2%
200	4.07	10.09	41.03	3.25	42.64	32.80	3	123.10	98.40	79.9%	87.19	88.6%	70.8%	74.47	75.7%	60.5%
Total Daily								1577.19	1438.50	**91.2%**	1080.07	75.1%	**68.5%**	922.56	64.1%	58.5%

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of decrease and increase in irradiance due to the interposition and removal of cloudiness in relation to the power loss during the cloudy period (in which the cloud totally interferes with the sunlight). In the same way, the peaks due to the cloud edge effect [44] do not result in a relevant increase in hydrogen production in our case.

On the other hand, the commercial electrolyzer operate in a wide range of power supplied (currents between 6 and 60 A); with these devices, working at low power yields higher performance although, obviously, with lower hydrogen production. If electrolyzers with more operating limitations are used, control systems, as a cutoff devices, surge suppressors or even intermediaries such as batteries should be incorporated. Several steps further are necessary in the regulated systems [43] which, with their pros and cons, are not the object of the present work, intended for application in small off-grid installations.

According to this, the average efficiency obtained for the electrolysis stage, 75.1% (Table 4), corresponds well with the values reported in the literature (60%–82%) [37,39,40].

On the other hand, the conversion devices involve losses of 2–6%, and up to 10% [14,43], which means that our value obtained for the joint efficiency of PV-electrolyzer of 91.2% can be considered really good for off-grid small devices.

The efficiency of the complete system for the production of hydrogen depends strongly on the photovoltaic conversion stage. The increase in efficiency of this stage is expected, which for commercial devices is between 15 and 30%, while cells with best performances remains today at laboratory scale [6].

In addition, the influence of temperature must also be considered. For qualitative considerations, the curves at 20 °C and 60 °C corresponding to the maximum irradiance have been included in Fig. 4: It is observed that in this temperature range the voltage deviation at the point of maximum power is only about 10%.

Conclusions

Based on theoretical considerations that consider the actual behavior of photovoltaic modules and electrolyzers, it is possible to establish a self-regulated interconnection that shows a very good performance.

We have shown that for small and low-cost applications, it is possible to eliminate any control system with yields of up to 91.2% at the PV-electrolyzer interface, and the average total efficiency reaches 68.5% if that of the electrolysis step (75.1%) is considered. This is a very good result in light of the benefits associated with handling simple systems, especially for isolated locations in developing countries.

Self-regulated "tuned" systems look like an efficient and simple modular alternative because they employ a minimum of control elements; this makes them particularly valuable for high-reliability low-power systems. These systems are environmentally friendly not only by the energy savings in the process, but also by the lesser need of components to achieve an efficient energy conversion.

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